Performance Evaluation of High Speed Surface Craft with Reference to the Hysucat Development

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BY

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Performance Evaluation of High Speed Surface Craft with Reference to the *HYSUCAT* Development

by

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1) Introduction

The development of the Hydrofoil-Supported-Catamaran, called the Hysucat as reported in [1], resulted in an efficient new type High-Speed-Surface Craft (HSS-Craft) with considerable lower propulsion power requirement than conventional craft.

Several model test series, a sea-going model and many commercial Hysucat's, the largest being the 18m Hysucat *H18* with 35,6t displacement and a maximum speed of 38 knot, have proved the Hysucat to be a practical, sea-friendly and economical rough water craft.

In the present evaluation process, in which the Hysucat principle has to be compared to other HSS-Craft, it was found that the practical methods in use today do not allow a comprehensive comparison of craft of different types. The comparisons based upon resistance evaluations are not sufficient for a final and total performance evaluation. Many of the practical methods make use of parameters which are not clearly dimensionless.

The air cushion vehicles, for example, have very low resistances indeed, but also need power to create the cushion pressure, which has to be incorporated in any evaluation.

A performance evaluation of HSS-Craft based upon propulsion power and energy consumption was, therefore, developed and a number of typical HSS-Craft, for which published data are available, taken into comparison with the Hysucat.

The main performance data of these Craft are listed in Table 1 together with the evaluation parameters and are also shown in the diagram in Fig. 4, which allows the relative merits of a new design proposal to be evaluated in relation to existent and successful HSS-Craft. The determination of the evaluation parameters is based upon a minimum of craft main data and can easily be performed by any ship designer or operator for the evaluation of any type of HSS-Craft.

The performance evaluation of several Hysucat designs, which were taken into consideration, indicates that this new HSS-Craft principle is one of the most efficient hull concepts and considerably improves above the Deep-V-Planing Craft, which is the hull-principle mostly used for the smaller craft.

Using the Hysucat principle, craft which have to fulfill similar tasks can be built with about 40% reduced propulsion power and be operated over the life span with about 40% reduced fuel consumption. The sea-keeping in rough seas is also strongly improved due to the catamaran concept.

The Hysucat is built up of conventional materials and HSS-Craft methods and uses commercially available and approved elements of the Marine Industry (Diesel Engines, Gears, Shafting, Propellers or Water-jets) and considering the High Technology of Hovercraft, SES- and Hydrofoil Craft designs, the Hysucat presents one of the most economical and efficient HSS-Craft principles.

By further systematical Hysucat design development, further improvements seem feasible, whereas conventional craft are fully developed.

2) *The Hysucat Principle*

The abbreviation Hysucat stands for Hydrofoil-Supported-Catamaran and describes a new craft, which consists of a combination of a planning catamaran hull and a hydrofoil system between the two fully asymmetrical demi-hulls. The logical development of the new craft is described in detail in the introduction (1). The drag-lift ratios of a dynamically supported craft presents a load carrying efficiency and is used in aircraft design as well as in High Speed Surface Craft design, wherein

$$e = D / L$$

with e = resistance coefficient
D = drag force
L = lift force

The resistance coefficient of high speed planing catamarans is in the order of $e = 0,25$ to $e = 0.30$, whereas the hydrofoil wing in near water surface mode has a much lower resistance coefficient of about 0,03 to 0,05. The hydrofoil is considerably more efficient to carry a load at high speed than the planing hull.

A combination of the planing catamaran with a hydrofoil, therefore, must result in a considerably improved craft. In this combination it is intended to place only a part of the total weight of the craft on the hydrofoils with the hulls still "actively working", which is different from the Hydrofoil Craft philosophy wherein all the weight is supposed to be carried at speed by the Hydrofoils and the hulls are carried as passive "deadwood". To achieve a well-functioning Hysucat, the two elements must be properly combined to reduce the resistance optimally, but, also to produce sufficient longitudinal and transverse stability and course holding ability.

At low speeds, the load is mainly carried by buoyant forces whereas, at high speed, the larger portion of the load is carried by dynamic forces. This means, that at different speeds, the lift force is built up of physically different force components. This has a strong effect on the longitudinal stability over the speed range and can lead to undesirable trim actions by the craft, if not properly accounted for in the design.

This problem was solved in the Hysucat design by the use of the tandem hydrofoil system, consisting of a main-foil near the longitudinal center of gravity (LCG) position and a trim-foil near the transoms. This so-called Avion-Hydrofoil-System provides an automatic trim stabilization at speed, when the hydrofoils operate in the so-called surface-effect-mode, which means, the lift forces reduce gradually by approaching the water surface from underneath. This way the trim stabilizing forces are strongly dependent on foil submergence and less on craft trim angle t.

Additionally, the hydrofoil action when running in sea waves at speed results in a damping effect of the vertical motions, as described in (1) and proved through tests on a 5,6m sea model Hysucat. The recognized good sea-keeping of the catamaran was further improved by the hydrofoils and less vehement vertical motions and smooth running in rough seas were observed on the manned sea model. The large transverse stability reserves of the catamaran allow narrow turning circles even in extremely rough water. The investigated Hysucat hull forms, so far, present all rough water designs. Sheltered water designs could have slightly different demi-hull forms with lower deadrise angles and reduced friction force components.

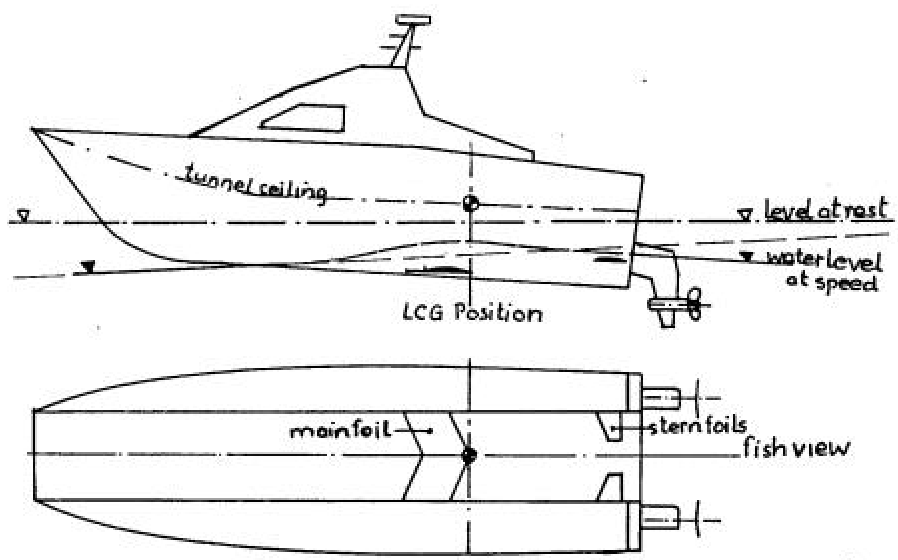

Fig. 1 : Hysucat Arrangement

A typical Hysucat foil system arrangement is sketched in Fig. 1 with the main-foil near the LCG position having a slight sweep and two smaller trim foils near the transom. The trim-foils are set slightly higher above the keels to allow operation in surface effect mode at speed, when the catamaran hulls run optimally with a slight trim angle t.

On an example of a model test in (1), it was shown that the resistance in smooth water due to the hydrofoil support system was only 34% of the same catamaran hull without foils. Against Mono-Planing-Hulls of the Deep-V-Type, the measured improvements were 40% to 50%.

The Hysucat principle was practically approved with the 5,6m BMI Hysucat manned sea model in sea test runs over a year in the sea off the Cape with strongly varying weather and wave conditions from smooth to extremely rough.

The BMI Hysucat did not show any shortcomings as a rough water craft and proved extremely sea-friendly, economical and could survive most severe conditions without the slightest default. It proved the Hysucat principle to be fully acceptable with the promised advantages of low propulsion power, low fuel consumption and improved sea-keeping.

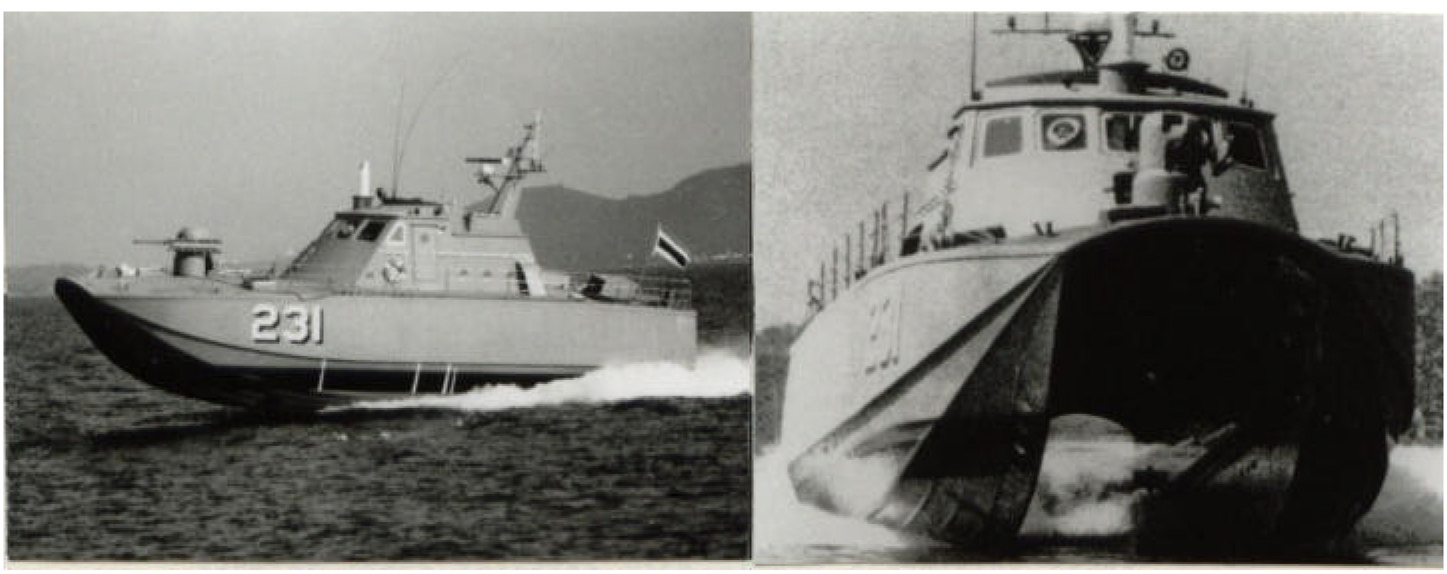

Fig. 2 : Hysucat 18 at Speed

Several commercial craft were designed and built. The smaller ones, up to about 10m, are driven by outboard engines. The largest one built so far is the H18 Coastal Patrol Craft designed in collaboration with Hysucat-Engineering Germany and built by Technautic-Intertrading-Shipyard in Thailand, see (1, 2). The H18 displaces 35,6t fully loaded and achieved 36 knot continuous with the two MWM TB 234 12 cylinder Diesel engines (P_b 100% = 620 KW each) and the V-drive-inclined-shaft propulsion systems on the initial shipyard trial runs. With different propellers, a speed of 38 knot was reported at a later stage, but the test conditions are not available to the author.
Fig. 2 shows the H18 at speed. Since then, the H18 operates successfully off the coast of Thailand.

Larger craft, up to 30m, have been designed, but have not yet been built.

The Hysucat principle has proved to allow most economical and successful HSS-Craft designs and further improvements seem possible by systematical design optimization.

More recently, the 10m Twin Hull Game Fishing Boat, Lady K, built by T-Craft Marine of Cape Town, has been converted to a Hysucat and a maximum speed gain of over 43%, due to the Avion Hydrofoil System installation , has been reached with the craft otherwise unchanged and the water-jets not re-trimmed, which is discussed in 3.3.

The present report is aimed at establishing a general performance evaluation of the Hysucat principle in the family of other HSS-Craft. As a fully satisfying general performance evaluation method is not available, it has been tried to develop a new method and apply it to HSS-Craft and the few Hysucat designs for which data are available.

3.) ***Performance Evaluation Methods***

3.1) Propulsion Power

The propulsion power system of a HSS-Craft has a strong influence on the total cost structure. The capital and running costs increase with larger propulsion power. The craft performance is also strongly dependent on the propulsion power requirement and a HSS-Craft with large propulsion power can carry less payload and has a reduced range due to the necessary high fuel reserves. In any HSS-Craft construction low propulsion power is a necessary design request. Many new craft types have been developed in the past in order to achieve HSS-Craft designs with lower propulsion power requirement, as Hydrofoil Craft, Hovercraft, Side-Wall-Aircushion-Vehicles, Catamarans with wave-cancellation effect and many more.

The efficiency of a HSS-Craft is best evaluated by propulsion power considerations. The main parameters influencing the HSS-Craft propulsion power requirement are the craft's total mass $?_M$ and speed V, the hull shape and propulsion system. For the evaluation, the required propulsion power of a HSS-craft has to be brought into relation to a basic power parameter P_{base} , which applies to all HSS-Craft in a similar way.
The fictitious power:

$$P_{base} = ? * V \quad (KW), \qquad (1)$$

with the displaced weight ? in kN and the ship-speed V in $^m/_s$, presents such a parameter. The base power P_{base} has no direct practical meaning, but could be imagined as the power necessary to run a craft against the force of gravity at design speed V, vertical up in vacuum. The base power is only dependent on the craft's total weight ? and speed, which depends on the acceleration of earth g and the craft mass, which are about constant for all craft operating at sea level height and the very small local deviations of g are negligible.

The propulsion power P_b at the Diesel engines crank shaft (or corresponding units for different prime movers) in relation to the base Power P_{base} presents a HSS-Craft efficiency parameter in dimensionless form. The ratio of the two power parameters is called the Power-Ratio e_p and is defined as:

$$e_p = \frac{P_b}{P_{base}} = \frac{P_b}{? * V} \qquad (2)$$

with ? in kN and V in $^m/_s$, P_b and P_{base} in KW. The lower the Power-Ratio e_p of a HSS-Craft, the more efficient the craft will be, indicating the smallest propulsion power requirement for a given base power.

The propulsion power requirement P_b is worked out in the design and measured during the trial runs.

It contains the efficiency of the propulsion system and follows to:

$$P_b = \frac{P_e}{P.C.} = \frac{R_t * V}{P.C.} \qquad (3)$$

with P_e = effective power and P.C. = propulsive coefficient (all-over-propulsion efficiency), R_t = total resistance force, often measured in a model test and correlated to the prototype.

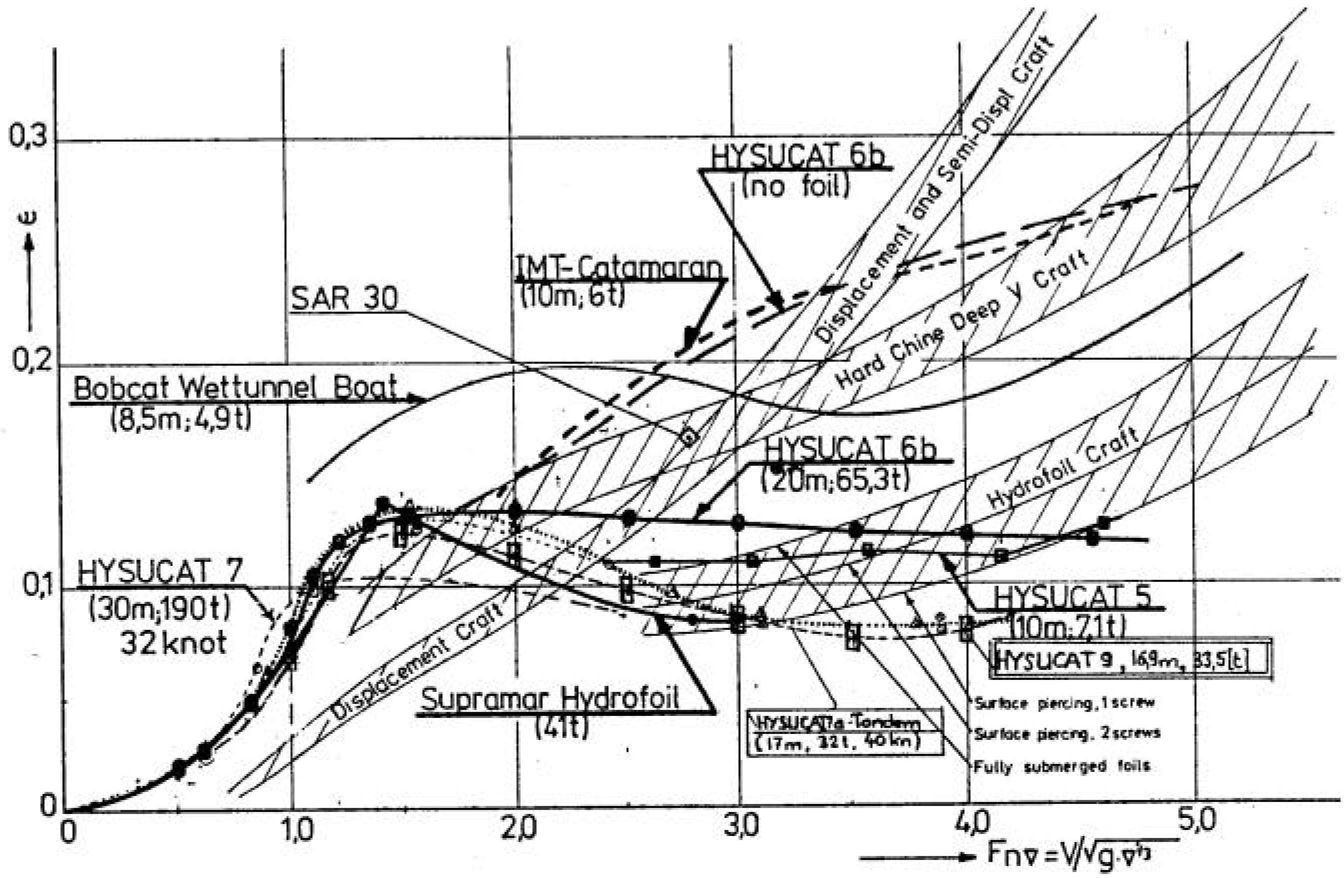

Fig. 3 : Resistance Displacement Ratios of Sea-craft

The total resistance in dimensionless form:

$$e \quad = \quad R_t \;/\; ? \qquad\qquad (4)$$

is often used to evaluate the craft against other craft. A typical diagram of the dimensionless resistance e over the dimensionless speed,

$$F_{n\urcorner} \quad = \quad V \;/\; v\,\overline{\;g * \urcorner^{\,?}\;}$$

for various craft is shown in Fig. 3, which also includes typical tendency curves for Semi-Displacement-Craft, Hard Chine Deep-V-Craft and Hydrofoil Craft. As it does not contain the propulsion characteristics, it is useful only for hull comparisons and does not always give a complete picture, as all resistance components are not always included. For example, Deep-V-Planing Craft are usually presented without their appendage resistances for propeller struts, inclined shafts and rudders included, Hydrofoil Craft often without the air resistance and so on. For air cushion craft, the power to create the air cushion remains unconsidered.

The resistance evaluation method is therefore not a comprising method and only useful for hull evaluation of similar craft.

Evaluation methods based upon the Power-Ratio e_p are more complete and the presentation of e_p over the Froude-Displacement Number $F_{n\urcorner}$ for the design conditions (or, eventually the service conditions) as shown in Fig. 4 gives the most objective comparison of the hydrodynamic performance of different HSS-Craft.

For the Power – Ratio e_p with Equations (3) and (4) follows:

$$e_p \quad = \quad \frac{P_e}{P.C. * ? * V} \quad = \quad \frac{V * R_t}{P.C. * ? * V} \quad = \quad \frac{e}{P.C.} \qquad (5)$$

the inverse of which is also called the transport efficiency, see Wright (3).

The Propulsive Coefficient P.C. is the overall propulsion efficiency and for a propeller driven craft built up by the propeller efficiency $?_P$, the wake-and-thrust deduction efficiency (called hull efficiency) $?_h$, the relative rotating efficiency $?_r$, the appendage and trim influence efficiency $?_A$ and the transmission efficiency (shaft bearings and gears) $?_m$.

$$P.C. \quad = \quad ?_P * ?_h * ?_r * ?_A * ?_m \qquad (6)$$

To elaborate the Power-Ratio Evaluation Method, the data of various HSS-Craft were collected from publications and are listed in Table 1, where the considered craft are numbered and given with their names or designations, builders, the necessary main data (displacement, speed, propulsion power), the evaluation parameter e_p and a Hydrodynamic Performance Rating H.P.R. which is defined as

$$H.P.R. \; = \; F_{n\nabla} \; / \; e_p \qquad (7)$$

for the design conditions, which presents the hydrodynamic performance quality of the craft at design speed (trial or service speed) in form of a single number. The higher the H.P.R number, the more efficient the craft can be considered, meaning that the highest speed is reached with the lowest power installed. The comparison of the H.P.R. number of different craft allows the fastest and most comprehensive hydrodynamic performance comparison if all the data are upon trial (or design) data. The results shall be discussed later. The above evaluation is perfect, when all the data are based upon controlled conditions as for trial runs or as elaborated in the design. Often such accurate data are not published for HSS-Craft and then the rated power of the installed engines are used. This can lead to unfavorable comparisons for such craft as the engine capacity is often larger than the power used for the trial runs and reserves are kept for acceleration or rough water running reserves. The data, therefore, must be used with caution. The indicated maximum speed of HSS-Craft is often useless as it might have been reached with the craft as light as possible and no fuel reserves on board. The proper design or trial speed has to be preferred and if not available, the service speed under service conditions was used to build up Table 1.

Table 1

Hydrodynamic Performance Comparison of High-Speed-Small-Craft

(Code for Fig.4)

Sym.	Nr	Name of Craft	Builder	Δ[t]	V[knot]	P[kw]	Fn∇	ep	H.P.R.
		Round bilge Displacement and Semi-Desplacement Craft							
□	1	Type S 143	Lürssen	375	38	13235	2,33	0,184	12,54
□	2	PB	Italy	1361	15	4706	0.74	0,046	16,11
□	2a	Shergar, Lürssens	Bremen - Germany	188	45,5	11290	3.13	0,262	11,92
		Deep - V - Planning Craft							
⊙	3	PT	Damen	85	24	1847	1,88	0,186	10,12
⊙	4	Cohete	Lewi Dsgn	60	24	1544	2,00	0,213	9,38
⊙	5	SAR 33	Abekg&Rasm	250	40	13235	2,62	0,262	10,08
⊙	6	Zarcos 16	Lewi Dsgn	22	25	735	2,46	0,265	9,27
⊙	7	Zarcos 12	Lewi Dsgn	8	24	243	2,79	0,251	11,12
⊙	8	Nasty Class	Norway	83	44	4559	3,47	0,248	14,00
⊙	9	P2 000	G.B.	49	40	2118	3,44	0,214	16,00
⊙	10	P2 000 Dheeb AL Behar		49	36	1765	3,10	0,198	15,60
⊙	11	Intermar. Mk 55		165	50	10294	3,51	0,247	14,19
⊙	12	Ilikai	Lewi Dsgn	9	28	412	3,19	0,324	9,84
		Hydrofoil Craft							
Δ	13	PT 20	Supramar	33	34	810	3,12	0,143	21,82
Δ	14	PT 50	Supramar	63	34	1620	2,80	0,149	18,81
Δ	15	PT 75	Supramar	78,5	36	2420	2,86	0,170	16,83
Δ	16	PT 150	Supramar	150	36	5058	2,57	0,186	13,81
Δ	16a	PT 150	Supramar	150	36	with start.power boosting			
Δ	17	High PointPCH1	USA	120	48	4706	3,56	0,162	21,94
Δ	18	Tuccumcari	USA	58	53	2353	4,50	0,152	29,62
Δ	19	Plainview AGEH-1	USA	320	50	20588	3,15	0,255	12,32
Δ	20	PHM Nato Hydr.	Boeing	218	50	19265	3,35	0,350	9,52
		Recently built Craft and Catamarans							
⊙	21	Sea Link Cat. Ferry		50	29	1430	2,49	0,196	12,68
⊙	22	Jet Cat Ferry Jc-1		73	32,5	2100	2,62	0,176	14,86
⊙	23	EM1	China Sh. Tradg	78	37	3529	2,94	0,243	12,12
⊙	24	Dvora	Israel Airc. Ind.	47	34	2000	2,94	0,248	11,87
⊙	25	Olympic 76	Greece	50	30	1912	2,57	0,253	10,16
⊙	26	Span. Cust. Craft (with Ri.CaL Jets)		15	55	1470	5,76	0,353	16,31
⊙	27	Indonesian Wat.jet.	PT Kodja	4,09	28,3	172	3,68	0,295	12,47
⊙	28	P 1200	G.B.	13	36	810	3,86	0,343	11,25
⊙	29	Precision Offshore 17	Australia	22	38	1375	3,73	0,326	11,45
⊙	30	HYSUCAT 18	Tech.Thaild.	36,5	36	1240	3,25	0,187	17,5
⊙	31	HYSUCAT 9	Tank predict.	33,5	40	950	3,66	0,141	26,0
⊙	32	PT 14,5	Singap. S. + E.	23	30	934	2,93	0,268	10,0
⊙	33	HYSUCAT 27	Lürss.,Dsgn-Tank pred.	140	40	4412	2,89	0,157	18,4
⊙	34	Tropic Sunbird Cat.	SFB-Eng. Austr.	127	28	2320	2,05	0,129	15,89
⊙	35	Tassie DeviL 2001	Int.Cat.Tasmania	72	26	1660	2,42	0,148	16,35
⊙	36	AZ60	Azimut Italy	30	28	1118	2,61	0,264	9,88
⊙	37	Norsul Cat.	Fjelstrd. Norway	84	26	1956	2,04	0,178	11,50
▯	38	Hovercraft API. 88	G.B.	38,5	45	1338	4,03	0,153	26,30
▯	39	SES Norcat	Norway	85	36	2650	2,82	0,172	16,42
▯	40	SAH 2200	Slingsby Aviat, G.B.	6,8	32	140	3,83	0,131	30,20
▯	41	4000TD, Griffon	G.B.	12,8	38	588	3,76	0,260	15,67
▯	42	SES Jet Rider, Karlskronavarvef	Sweden	88,3	42	(90%)3582	3,27	0,192	17,07
⊙	43	Westcruiser	Norway	30,5	31	1103	2,88	0,231	12,47
⊙	44	Lady K, Wat.jet	T-Craft Cape Town	8,3	24,5	348	2,83	0,339	8,34
⊙	45	Lady K, Wat.Jet	T-Craft Cape Town	8,3	32	348	3,70	0,260	14,25

From the data in Table 1, a diagram was drawn presenting the Power-Ratio's e_p over the Froude-Displacement Number $F_{n\nabla}$, shown in Fig. 4. It contains the listed craft by numbers and also tendency curves for Semi-Displacement Craft, Deep-V-Planing Craft and Hydrofoil Craft, taken from (4), but converted to the parameters adapted in the present publication.

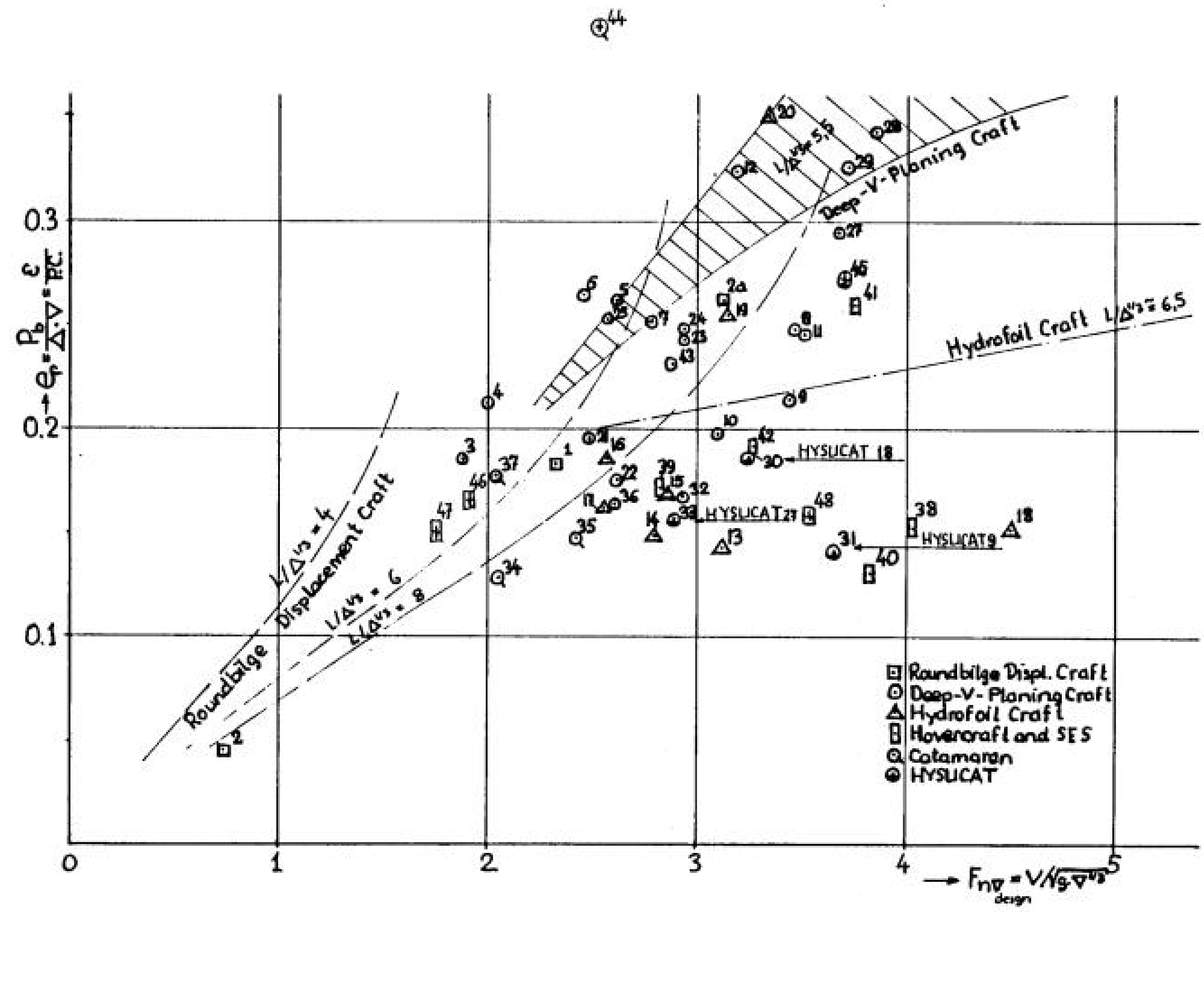

Fig. 4 : High Speed Surface Craft Power-Ratio e_p

By plotting the point of a design proposal, e_p over $F_{n\nabla}$ at design conditions, onto the graph in Fig. 4 it's position in relation to other successful HSS-Craft, which are already incorporated in the diagram, allows a comprehensive evaluation. Some examples shall be discussed later.

3.2) The Craft Specific Fuel Consumption Ratio

Fuel consumptions are usually measured during the trial runs. It is required by the operator to estimate fuel storage for later envisaged voyages for a given range.

The craft specific fuel consumption ratio C* is then determined for various speeds and loads and given as the mass of fuel consumed F_{fuel} per kilometer traveled and per unit mass of the ship in metric tons:

$$C^* = F_{fuel} / S_t * ?_M \tag{8}$$

with S_t = distance of travel in km,

and $?_M$ = displacement mass in t (lt = 1000kg)

The consumed fuel mass can be calculated when the propulsion power P_b is known and the specific fuel consumption of the Diesel Engine (or Otto Motor) C_e [kg fuel / kW.h] is available after workshop tests and follows to:

$$F_{fuel} = \frac{P_b * C_e * t}{3600} , \tag{9}$$

with t in seconds.

From Equation (8) and (9) follows:

$$C^* = \frac{C_e * P_b * t}{3600 * S_t * ?_M} \tag{10}$$

For the ship traveling at steady speed, the covered distance follows to:

$$S^{/}_t = V_s * t \quad [m] \quad \text{and}$$

$$S_t = \frac{V_s * t}{1000} \quad [km] \tag{11}$$

and with Equation (10) follows to:

$$C^* \; = \; 1000 * C_e * P_b \,/\, 3600 * V_s \quad \text{(with } V_s \text{ in m/s)}$$

and

$$C^* \; = \; C_e * P_b \,/\, 3{,}6 * V_s \; * ?_M \quad [\text{kg fuel / km} * \text{t}] \qquad (12)$$

The brake power at the Diesel crankshaft P_b is defined as:

$$P_b \; = \; \frac{R_t * V_s}{P\,.\,C.} \qquad (13)$$

with P.C. being the overall propulsion efficiency, called the propulsive coefficient. The dimensionless resistance is:

$$e \; = \; R_t \;/\; ? \quad \text{(both in KN)} \qquad (14)$$

The craft specific fuel consumption ratio follows with Equations (13) and (14) to:

$$C^* \; = \; \frac{C_e * e * \; ? * Vs}{P.C. * 3{,}6 * V_s * \; ?_M} \quad [\text{kg fuel/ } t_{displ}.\text{km}\,] \qquad (15)$$

which simplifies to:

$$C^* \; = \; \frac{Ce}{3{,}6\,.} \; * \; \frac{e}{P.C.} \; * \; \frac{?}{?_M}$$

$$\text{and with} \quad \frac{?}{?_M} \; = \; \frac{? * ?}{? * ?} \; = g, \quad \text{and} \qquad (16)$$

with g = acceleration of earth, it follows:

$$C^* \; = \; \frac{9{,}81}{3{,}6} \; * \; \frac{Ce * e}{P.C.} \; = 2{,}725 \; * \; \frac{Ce * e}{P.C.} \; \frac{[\text{kg fuel}]}{[\text{km.t}]} \qquad (17)$$

which reduces with Equation (7) to:

$$C^* \; = \; 2{,}725 * e_p * C_e \quad [\text{kg fuel / km} * \text{t}] \qquad (18)$$

Equation (18) proves that the Power-Ratio e_p, which was given in Table 1 and Fig. 4 for various craft, is directly related to the craft specific fuel consumption ratio C*, which presents the most comprehensive hydrodynamic performance efficiency of a craft, including hull-, propulsion- and engine efficiencies combined. This result is not unexpected as the fuel flow to the engines during craft operation contains all the energy that is consumed and must be the most complete indicator of the craft's efficiency.

The craft specific fuel consumption ratio C* can easily be determined accurately by measurements during craft operation without much equipment effort and costs. When the Diesel specific consumption C_e is known for the design or service condition Equation (18) allows the determination of the Power-Ratio e_p, which can be compared with the design value. If no good agreement is reached, the inefficient component in C* can be searched for, which could be the Engines (Tuning), Propulsion System (Propeller or Hull), which all contribute to the total efficiency C*.

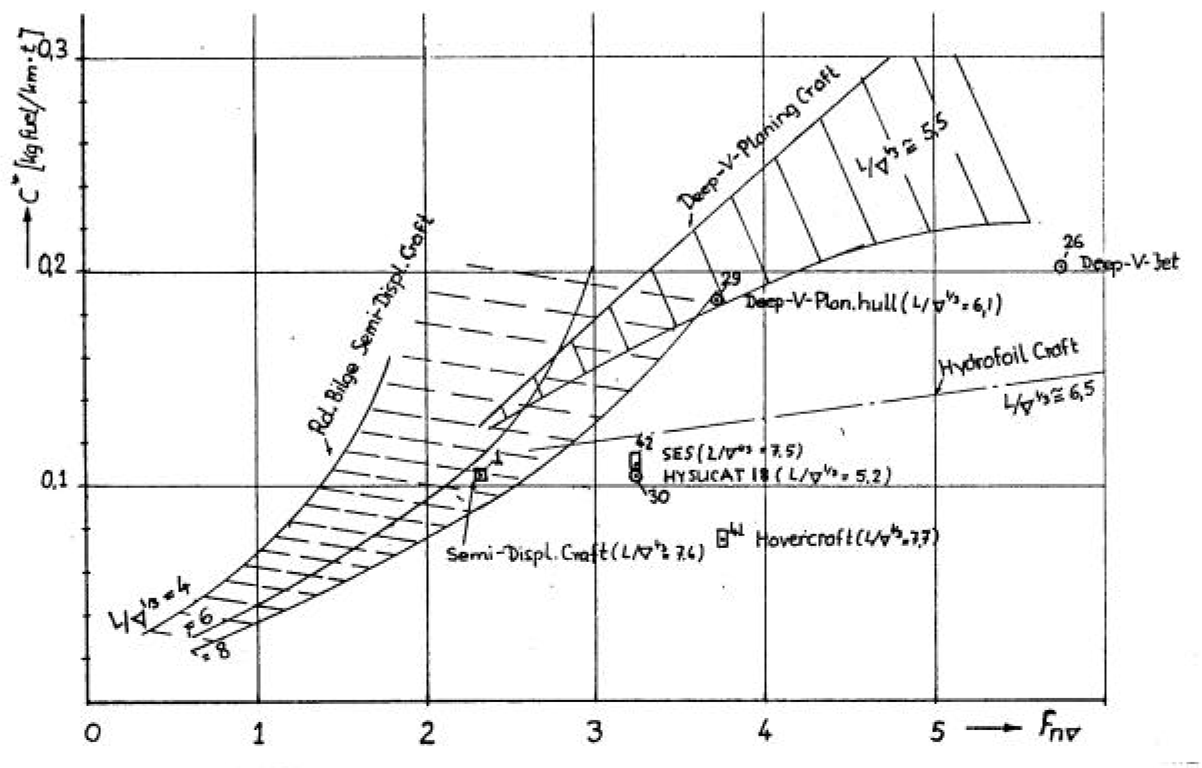

Fig. 5: High Speed Surface Craft Specific Fuel Consumption Ratios C*

For new craft design evaluation, the craft specific fuel consumption ratio C* at design speed (or for service speed in special cases) has to be measured and compared with the design value. A diagram, as indicated in Fig.5, with the craft specific fuel consumption ratio C* at design speed plotted over the Froude Displacement Number Fn presents the most comprehensive hydrodynamic performance evaluation method. This graph is drawn with the tendency curves of Semi-Displacement Craft, Deep-V-Planing Craft and Hydrofoil Craft based upon a Diesel specific consumption ratio of 0,210 [kg/KW. h], which presents about the best at the time. Fig. 5 also contains data points of a few typical craft to allow the evaluation of a new design proposal. The diagram could not be completed for all craft listed in Table 1 as the consumption data are usually not published and it should be built-up with measured fuel consumption data only, to give it more practical value. Once, when the measured C* data are incorporated in the diagram, Fig.5 presents a valuable performance evaluation sheet for HSS-Craft for the designer, the engineer in charge of the trial runs and the operator.

It can be argued that during the trial runs, the accurate specific Diesel consumption coefficient C_e is not known. It can be determined only when the rotational speed and load are also measured. From the design conditions, the approximate load is known and the specific consumption C_e of a Diesel engine does not change strongly with load changes in quite a wide range. For example, the MWM TB234 V12 has a 3,4% increased C_e-value for a load change of 34% from 605 kW to 450 kW at 2200 rpm.

Only for excessive load variations (reductions of more than 60%) will the C_e-value increase by 15%.

For design conditions, the real and design-load will not vary strongly and an assumed constant C_e-value for the Diesel engine will not introduce a large fault. The above MWM Diesel engine has a C_e = 0,200 kg Fuel/KW.h at high load and for 20% reduced loads about C_e = 0,208 at top speed and also lower speeds.

For craft evaluations, the Diesel engine specific fuel consumption ratio C_e, as measured in the workshop test, for design speed and design load conditions of the craft can be used with confidence and will give a reliable evaluation method.

The measurement of fuel consumption and the determination of the craft specific fuel consumption ratio C* for the craft operating in rough sea conditions could give a simple tool to evaluate the design proposal in point of view of sea-going efficiency. A diagram of C* in dependence of $F_{n\nabla}$ and the main sea conditions (direction of waves, height, length, etc.) will show the craft sea performance qualities.

Similar to the development of a single Hydrodynamic Performance Rating Number H.P.R, a consumption Rating Number C.R.N can be built up, defined as:

$$CRN = F_{n\nabla} / C^* ,$$

which will describe the hydrodynamic efficiency of the craft under consideration in the most complete form including the prime mover-, hull and propulsion efficiency.

The determination of the CRN is relatively simple and easy and can also be performed on the trial run of small craft. The lack of published consumption data prevents the further elaboration at this stage, but the required data will be collected for future comparisons.

3.3) *Comparison of HSS-Craft Types*

The HSS-Craft considered in the present evaluation attempt are listed in Table 1 with their main data, as found in current publications. The Power-Ratio e_p and the Hydrodynamic Performance Rating H.P.R were determined for every published craft as well as the data information allowed it.

The Fig. 4 shows the diagram containing the Power-Ratios e_p of the craft considered from which some general deductions are possible:

The HSS-Craft, which are all workboat type craft (racing craft are not included) operate with Froude-Displacement Numbers $F_{n\nabla}$ between 2 and 4. Very few craft operate at higher $F_{n\nabla}$ -values and if so, it seems to concern experimental or racing craft. The bulk of conventional HSS-Craft operates at Froude numbers of $F_{n\nabla} = 3$.

Semi-Displacement Craft follow the tendency curves e_p very closely and the main parameter is the slenderness degree, L / ?? . The higher the Froude-Displacement Number, the higher the slenderness degree has to be for a low Power-Ratio e_p. The Semi-Displacement catamaran allows higher slenderness degrees and can be run, therefore, at higher $F_{n\nabla}$, see Craft 22, 34 and 35.

The Deep-V-Planing Craft fall well in the range indicated by the tendency curves and have relatively high Power-Ratios e_p. Some of these craft around $F_{n\nabla} = 3$ (which indicates medium size craft) are slightly below the e_p-tendency curves, which might be due to efficient propulsion systems.

Hydrofoil Craft have distinctively lower Power-Ratios and fall well below the indicated e_p tendency curve, which seems to be outdated. The larger Hydrofoil Craft, over 100t, are less efficient and have relatively high e_p-values, an extreme being the NATO-Boing-Hydrofoil with gas turbine and water-jet propulsion.

However, this e_p-value, which falls in the field of Planing Craft, may be misleading as the value was determined with the installed propulsion power. The craft has eventually larger power reserves at top speed, but needs the large power plant for acceleration and to overcome the Hump resistance.

The smallest Supramar Surface Piercing Hydrofoil Craft with $?_M$ = 33t , point 13, seems to be the most efficient in this series with e_p = 0,143. The largest one with $?_M$ = 150t has a e_p = 0,186 at a lower Froude-Displacement Number. The SES have a slightly higher Power-Ratios e_p, between 0,17 and 0,19, with the exception of the Corsair, point 48, which has a much lower e_p = 0,14 and presents one of the most efficient HSS-Craft, probably due to the efficient Surface Propeller System.

The lowest Power-Ratios of craft considered, so far, is reached by Diesel propelled Hovercraft, point 40. However, this craft is relatively small and of extremely light build. The larger Hovercraft have an e_p = 0,15, see point 38 and 41.

The Hysucat 18 has a much lower Power-Ratio e_p than the Deep-V-Planing Craft and compares well with the SES Craft. Recently designed Hysucat's have Power-Ratio which compare well with Hydrofoil Craft data, see points 31 and 33 and approach the best Hovercraft values.

The Hydrodynamic Performance Rating H.P.R. values for each craft are given in Table 1. Fast Semi-Displacement Craft have H.P.R. values of around 12. Displacement craft can reach higher values at lower speeds and reach values around 16. The conventional Deep-V-Planing Craft have H.P.R. values around 10, but modern, larger craft can reach values of up to 16, see point 9.

Hydrofoil Craft have strongly varying H.P.R. values, mainly dependent on size, of 14 to 20 while some experimental craft have H.P.R. = 29,6, see point 18 (Tuccumcari).

The two referenced SES craft have H.P.R. = 16 to 17, the Corsair's H.P.R.= 25,6. Hovercraft reach H.P.R. values of 26 with one exception (craft 40), which has a H.P.R. = 30.

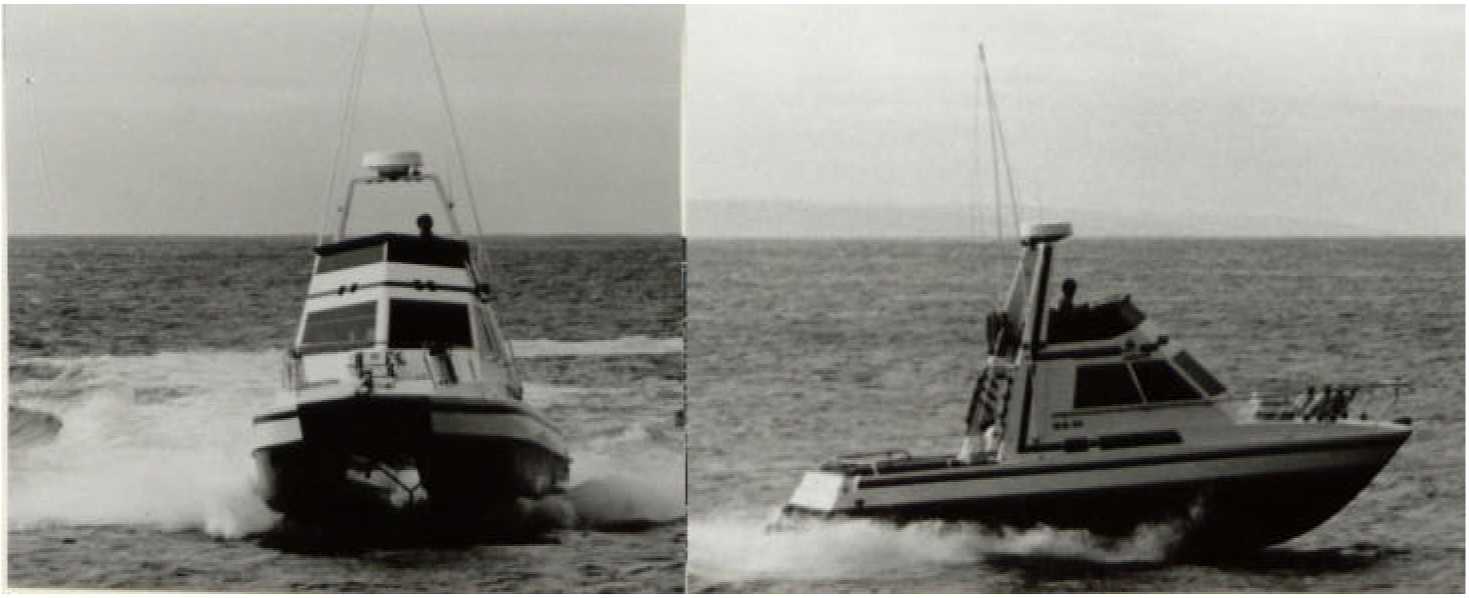

Fig.6: The 10 m T-Craft with Hydrofoil System at sea

The converted 10m T-Craft mentioned in chapter 2, has a catamaran hull with nearly fully asymmetrical demi-hulls and is therefore, suitable to be equipped with a hydrofoil-support-system.

The craft is propelled by two ADE Diesel engines developing 184 KW each and two Castoldi-Water-jets nr. 6 and displaces a mass of water of 8.3[t] under service conditions. Due to the hydrofoil system, the speed was improved from 22.0 knot before hydrofoil installation to 32 knot after. (In the Atlantic swell, wave speeds of over 36 knot were recorded.)

The craft remained completely unchanged for the two conditions and not even the water-jets were re-trimmed. The speed-gain is therefore, purely due to the hydrofoil action and presents a 40% improvement as can be seen from the performance evaluation parameter e_p in Table 1, craft numbers 44 and 45, also shown on the graph in Fig.4. From this graph, it can be seen that optimized Hysucat's can reach further improved e_p values of 0,16 to 0,18 , but depending strongly on the propulsion system used. However, it must be realized that the combination of a planing catamaran with water-jets will result in some efficiency restriction due to the water-jet efficiencies and especially for a conversion, which does not allow full Hysucat design optimization in the combination of the hull and hydrofoil elements.

However, the converted 10m T-Craft is now more efficient than a Deep-V-Planing Craft with propeller propulsion, see Fig. 4. Fig.6 shows the 10m T-Craft with hydrofoils at sea, the main-foil support strut being visible in the tunnel. The sea-keeping of the T10 is also improved with the craft riding higher out of the water with smoother motions and fully dry fore-deck in rough seas.

The water-jets provide an astonishing maneuverability at low speeds in the harbour as well as at high speeds on the sea. Further conversions are anticipated and a 12m and a 20m T-Craft with Hydrofoil-Support are under development.

The Hysucat's have H.P.R values of 17,5 to 26. This evaluation shows that the Hysucat principle, which is not developed to it's full potential, already compares well with the modern high technology craft. This becomes even more interesting if considered in view of the relative simplicity of construction of the Hysucat by use of commercially available HSS-Craft elements and building methods.

(3.4) *Hydrodynamic Performance and Costs*

The traditional saying in the Marine Industry that the speed of a ship is the most expensive parameter applies especially to High Speed Surface Craft, which are relatively small craft with high speeds in relation to the size. In other words, the Froude number is high. In spite of the high costs for the powerful propulsion systems and the connected high fuel consumption, the desire for higher speeds is increasing nowadays, which leads to the development of many new hull principles, new propulsion systems and more powerful and efficient Diesel engines. Any major advance in one of the three fields leads to major changes in the craft designs.

Higher speeds are possible by the application of more powerful engines. This method is usually followed up by industry immediately whenever possible, but is resulting in very expensive craft with extremely high running costs and reduced range. It can only successfully be applied to racing craft.

High Speed Surface Craft for commercial use have to be as efficient as possible to keep the capital costs (Diesel and Installation) and running costs (fuel consumption over life span of craft) to a minimum. The propulsion machinery on High Speed Surface Craft can take a share of up to 40% of the total construction costs and the consumption costs, which are strongly dependent on the oil price, a share of 30% to 50% of the total running costs (for small Ferry craft, this figure could even be higher).

An efficient craft with a low Power-Ratio e_p will be possible with smaller engines and therefore, has reduced capital costs to fulfill a defined requirement. It also has a lower fuel consumption. (C* is smaller) and will burn considerably less fuel over it's lifespan than a less efficient craft. The total costs will be considerably reduced.

There exists a direct connection between the two craft efficiencies e_p and C* developed in the previous chapters and costs, but a general cost efficiency development seems impossible and has to be conducted separately for every single craft. However, the craft efficiencies e_p and C* can indicate the cost tendencies.

The capital costs of the craft increase with the Power-Ratio e_p for any craft in a similar way. The running costs are strongly dependent on the operational requirements of the craft. A luxury yacht or pleasure craft, which is tied up in the harbour for most of the time, is little affected by the craft specific consumption ratio C*. For Patrol Craft, Rescue Craft or Ferry Boats, which are operational for a high percentage of time over their lifespan, the fuel consumption costs will present the highest share in the total cost structure and such craft should have the lowest possible Power-Ratio e_p and Craft Specific Consumption Ratio C*. The total costs will vary nearly linearly with variation in the consumption ratio C* (and approximately also with the Power-Ratio e_p as the commercially available Diesel engines do not vary strongly in specific consumption).
Then, it can be stated that a craft with an improved Power-Ratio e_p of, say, 20%, will save the owner 20% of the total costs over the ship's lifespan.

The cost tendency shall be elaborated by use of a constructed example:

A standard Deep-V-Planing craft with a displacement of 35t and a service speed of 38 knot is compared to a corresponding Hysucat with the same operational requirements. The Froude Displacement Numbers of both craft are:

$$F_{n\nabla} = 3{,}47$$

The operational time is assumed to be 5h per day in average, which means 1800 h/year and 120 096 km/year is covered.

The Deep-V-Planing craft at a Froude Number of 3,47 has a Craft Specific Consumption Ratio C* at best of C*= 0,175, whereas the Hysucat has a C* = 0,105 (see Fig. 5), from which it follows that the Deep-V-Planing craft consumption is:

$$C_{deep\text{-}v} = 0{,}175 * 35\ [t] * 120\ 096\ [km] = 735\ 059\ [kg\ fuel]$$

with R 1,08 / kg fuel*, this results in costs of R 793 863 per year.

The Hysucat will burn off:

$$C_H = 0{,}105 * 35 * 120\,096 = 441\,353 \text{ [kg fuel]}$$

at a cost of R 476 662 per year. The savings due to the higher craft efficiency of the Hysucat are R 317 774 per year**.** The Deep-V-Craft will burn fuel in the value of the craft capital costs in about 4,4 years, the Hysucat in only 7,3 years.

The 10m T-Craft conversion is a Hysucat mentioned in (Chapter 2) and (Chapter 3.3) and results in cost savings as follows:

The T-Craft without hydrofoils with 3,5 h/day average operation time results in 1260 h/year with 51 337 km covered and with an e_p = 0,378 from Table I, has a craft specific consumption ratio by use of Equation (18) and a Diesel specific consumption of 0,240 kg/kW.h of :

$$C^* = 0{,}378 * 0{,}240 * 2{,}725 = 0{,}2472$$

which results in a total consumption of

$$C_{T\text{-craft}} = 0{,}2472 * 8{,}3 * 51337 = 105\,336 \text{ kg fuel/year}$$

which costs R 113 763 per year.

For the same distance covered, the T-Craft Hysucat conversion, the Craft Specific Consumption Ratio follows to:

$$C_{T\text{-craft } H} = 0{,}26 * 0{,}240 * 2{,}725 = 0{,}170$$

with a resulting consumption of

$$C_{T\text{-craft } H} = 0{,}170 * 8{,}3 * 51337 = 72436 \text{ kg fuel}$$

at a cost of R 78 231 per year.

*Fuel price at Cape Town Yacht Club, Jan 1990. Commercial Craft are subsidized with 25%.

A saving on R 35 532 per year, can be expected due to the conversion and a reduction of operational time of about 40% , which increases the lifespan of the engines and the craft in general and it's useful working time. With higher operational time and higher fuel prices, the savings increase proportionally. For commercial craft, all price figures are reduced by 25% due to subsidy.

In the construction costs, the propulsion system has a considerable share, which is for the water-jet-powered 10m T-Craft in the order of 50% (including complete installation). Would it be tried to achieve the same speed of 32 knots with the T-Craft as is reached with the T-Craft conversion, an increased propulsion power of about 2 * 308 KW would be necessary, which would increase the costs of the Diesel engines by about 77% and the total craft costs by about 38,5% , slightly lower than the improvement in the Power-Ratio e_p.
The above examples show how sensitive the cost structure of High Speed Surface Craft is in relation to the craft hydrodynamic efficiencies, presented here as Power-Ratio ep and Craft Specific Consumption Ratio C*.

(4) *<u>Conclusions</u>*

A method to elaborate the hydrodynamic performance of High Speed Surface Craft was developed in the form of the Power-Ratio e_p, which presents the required propulsion power of the craft over a fictitious base power, which is the power to run the craft at design speed against the gravity force of earth (in vacuum), which is clearly defined for any craft and given by ? $*$ V . The Power-Ratio e_p is also known as the transport efficiency and defined by:

$$e_p = P_{propulsion} \;/\; ? * V \;=\; e \,/\, P.C. \;,$$

it contains the influence of the ship hull and the propulsion system on the propulsion power requirement. The data of over 40 High Speed Surface Craft were collected from publications and listed in Table 1, wherein also the Power-Ratio e_p and the dimensionless speed, the Froude Displacement Number $F_{n∇}$ are listed. A further performance parameter, the so-called Hydrodynamic Performance Rating H.P.R., which is defined as the $F_{n∇}$ / e_p and which gives a performance comparison parameter in a single number (the highest design speed at the lowest design propulsion power as best value) is also listed. The larger the H.P.R., the better the craft! Table 1 allows direct comparisons of all the craft incorporated with new design proposals.

The data are also plotted in Fig. 4 as a diagram of e_p over $F_{n∇}$. Tendency curves for Semi-displacement craft, Deep-V-Planing craft and Hydrofoil craft are incorporated. All craft are presented by a point with the listing number. If a new design proposal has to be compared to successful HSS-Craft, the design values of e_p in relation to known and other successful craft become visible. The tendency curves show the expected field for the specific craft.

Hydrofoil Craft, Hovercraft and SES have considerably lower e_p values than fast Semi-Displacement Craft or Deep-V-Planing Craft in the high speed range. The Hysucat has e_p values which compare well with the best craft in the diagram and are as good or better than SES Hovercraft and Hydrofoil Craft. This proves that The Hysucat is one of the most efficient HSS-Craft principles. Later designs, which have not been built yet, are already much better than the Hysucat 18, which is in operation.

By further optimization of the propulsion system, the Hysucat e_p-values can be expected to be improved by about 15%, which could make the Hysucat the most efficient HSS-Craft principle, especially in view of the simplicity of construction against the other high technology craft.

A performance parameter, based upon fuel consumption measurements, was developed and it was found that the craft specific fuel consumption ratio:

$$C^* = \text{kg fuel / km} * \text{t - displacement}$$

presents the most comprising hydrodynamic performance parameter as it also includes the characteristics of the prime-mover. It could be shown that the Power-Ratio e_p is connected to the craft specific fuel consumption ratio C* by the equation (18), namely:

$$C^* = 2{,}725 \; * \; \frac{e}{P.C.} \; * \; Ce = 2{,}725 \; * \; e_p \; * \; Ce \quad [\text{kg fuel/km.t}]$$

The fuel consumption of a craft is easily and accurately measured on trial runs or in service and the craft specific fuel consumption ratio C* can be calculated for the design speed. A diagram, shown in Fig. 5, C* over $F_{n\nabla}$ would give the most comprising comparison of HSS-Craft. Tendency curves and also example points are incorporated to allow an early comparison. Otherwise, the diagram shall be completed with “measured consumption” data only to allow practical comparisons. The tendency curves were calculated by use of good Diesel Engine Consumption ratios of C_e = 0,210 kg fuel/KW h.

The Semi-Displacement Craft, see point 1, falls well within the corresponding tendency curve and the example of a Deep-V-Planing craft, point 19, in the range of tendency curves of Deep-V-Planing Craft. SES and Hysucat have much lower C* values, lower than the general Hydrofoil Craft tendency curves. The best C*-value is reached by a small single Diesel engine driven Hovercraft, see point 41.

A Rating Number R.N.C. (Rating Number Consumption) based upon the craft specific consumption ratio and the Froude Number, defined by R.N.C = $F_{n\nabla}$ /

C*, is to be built up when more consumption measurements at design speed become available. For the typical Deep-V-Planing Craft, see point 29, the R.N.C = 20,05, for the SES, see point 42, R.N.C = 29,72, for the Semi-Displacement Craft, see point 1, the R.N.C = 22,2. For the best Hovercraft, R.N.C = 51,07 and for the Hysucat 18, the R.N.C = 31,6, for the Hysucat 9, see point 31, the R.N.C = 45,4.

The presented performance evaluation method was developed to compare the new HSS-Craft Hysucat with the existing and well-developed Craft in use today. The Hysucat takes up a very favorable position and must be considered one of the most efficient HSS-Craft principles.

The relatively small HSS-Craft with relatively low project costs often do not allow full performance evaluations during trial runs including thrust and shaft power measurements.

It is hoped that the present Performance Evaluation Method can assist in the evaluation of future HSS-Craft. The craft specific fuel consumption ratio C* must be looked at as the most comprising parameter.

(5) Literature

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